Risk Factor of Inadequate Food System

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If the food system does not adequately provide for food safety, nutrition and taste, then crew health and performance and the overall mission may be adversely affected. Furthermore, if the food system uses more than its allocated mission resources, then total required mission resources may exceed capabilities, the mission deemed unfeasible, or allocation of resources to other systems may be unduly constrained. – *Human Research Program Requirements Document*, HRP-47052, Rev. C, dated Jan 2009.

Executive Summary of Evidence for Risk

An adequate food system is required to enable safe, reliable, and productive human space exploration. This food system will be required to deliver safe, nutritious, and acceptable provisions to the crew while efficiently balancing appropriate vehicle resources such as mass, volume, waste, and food preparation time for Exploration missions. A dual system consisting of a packaged food system (with a shelf life of 3 to 5 years) and a bioregenerative food system on the planetary surface is being considered for the Mars missions. Understanding the potential risks to the food system for long-duration missions is an important step on this path.

The safety of food is of highest importance as the incidence of food-borne illness could compromise the success of a mission. While current pre-flight procedures have ensured food safety so far, the ongoing development of the mission architecture for lunar and Mars explorations necessitates a reexamination of these existing procedures as well as the development of new processes.

Since the food system is the sole source of nutrition to the crew, a significant loss in nutrition, either through the loss of nutrients in the food or inadequate food intake, may also significantly compromise the performance of the crew. The nutritional content of the food may be inadequate due to losses during processing or environmental factors (e.g., temperature and radiation) encountered over the shelf life of the food. Providing adequate levels of acceptability, variety, and usability is important to prevent inadequate caloric intake.

The ineffective use of vehicle resources such as mass, waste, and crew time can affect mission success. The mass of the packaged food system is based on the mass of the food and the packaging surrounding the food, which could produce a significant amount of waste. A bioregenerative food system that could provide the crew with fresh foods will use more crew time so the benefit to the performance of the crew must be shown to offset this additional burden.

The paramount importance of the food system in a long-duration human Exploration mission should not be underestimated. Vehicle resources must be balanced with safety, nutrition, and acceptability to provide an adequate food system. The food system will provide not only the nutrients that will be needed for the survival of the astronauts, but also will enhance the psychological well-being of the crew by serving as a familiar element in an unfamiliar and hostile environment.

This document presents the evidence that supports the risk factor of [an] inadequate food system as well as the knowledge gaps that still remain and that need to be filled.

Introduction

The primary goal of the Advanced Food Technology (AFT) Project is to develop requirements and technologies that will enable NASA personnel to provide an adequate food system that is characterized by the provision of safe, nutritious, and acceptable food while also efficiently balancing appropriate vehicle resources such as mass, volume, waste, and crew time in the Exploration missions. AFT, which is a project within the Space Human Factors and Habitability (SHFH) Element, is expected to directly relate to the Human Research Program (HRP) objective of developing capabilities and technologies in support of human space exploration, focusing on mitigating the highest risks to crew health and performance. Further details on the HRP can be found at http://humanresearch.jsc.nasa.gov/about.asp.

The authors of space program food system literature have documented the evolution of the space food system. Several types of food and beverage packaging have been used in NASA space programs. With the exception of Skylab, there has not been a refrigerator or freezer on board that was dedicated to food storage. Therefore, the food must be shelf-stable. This requires inactivation of the microorganisms in the food during ground processing before flight. While processing the packaged foods to commercial sterility provides a safe food system, this level of processing can reduce the quality of the food, including nutritional content and acceptability.

The different forms in which food has been provided include the following:

1. *Thermostabilized* – This process, which is also known as the retort process, heats food to a temperature that renders it free of pathogens, spoilage microorganisms, and enzyme activity. Food items are placed in cans or pouches and are heat processed with steam- or water-overpressure to remove excess air/oxygen for specified times and temperatures to render the food commercially sterile.
2. *Irradiated* – Although irradiation is not typically used to process foods to commercial sterility, NASA has special dispensation from the Food and Drug Administration (FDA) to prepare nine irradiated meat items to commercial sterility (21CFR179, 2008). Irradiation involves the use of gamma rays, x rays, or electrons, and uses energy levels that assure the negative induction of radioactivity in the irradiated product. It controls naturally occurring processes such as ripening or senescence of raw fruits and vegetables, and is effective for inactivation of spoilage and pathogenic microorganisms.

3. *Rehydratable* – A number of technologies are available that allow for the drying of foods. Examples of these technologies are drying with heat, osmotic drying, and freeze drying. These processes reduce the water activity of foods, which results in the inability of microorganisms to thrive.
4. *Natural form* – Natural form foods are commercially available and shelf-stable. The moisture of the foods may range from low moisture (e.g., almonds and peanuts) to intermediate moisture (e.g., brownies and dried fruit). These foods rely on reduced water activity to prevent microbial activity.
5. *Extended shelf-life bread products* – Items such as scones, waffles, and dinner rolls can be formulated and packaged to give them a shelf life of up to 18 months.
6. *Fresh food* – Fresh fruit, vegetables, tortillas, and other foods that have a short shelf life are provided on a limited basis, more for psychological support than as part of meeting dietary requirements.
7. *Beverages* – The beverages currently being used on the International Space Station (ISS) and shuttle are either freeze-dried beverage mixes (e.g., coffee or tea) or flavored drinks (e.g., lemonade or orange drink). The drink mixes are prepared and vacuum-sealed inside a beverage pouch. In the case of coffee or tea, sugar or powdered cream can be added. Empty beverage pouches are also provided for drinking water.

One of the goals of the Constellation Program (CxP) lunar long missions is to use the lunar surface as a test bed for future Mars missions. Although it is possible for CxP mission planners to continue using current food technologies, a change in missions will necessitate a change in the food system. The CxP missions will require longer shelf-life packaged foods with improved nutrition and acceptability. These missions will also require more attention to resource utilization such as mass, volume, power, crew time, and water use. The Mars missions, in particular, will require that technologies be developed so that the crew is more self-sufficient and less dependent on resupply missions. In addition, once the crew is out of low Earth orbit, space radiation is higher, and space-irradiated food may lose nutritional content and acceptability. The research that AFT conducts will allow for the food system to change when necessary.

To further address the limitations in vehicle resources to accommodate prepackaged foods, mission designers also envision that once the crew is on the lunar or Mars surface, crops will be grown. Fresh fruits and vegetables, such as spinach, lettuce, tomatoes, carrots, bell peppers, onions, potatoes, and strawberries, could be grown hydroponically in environmentally controlled chambers. In addition, baseline crops, such as soybeans, wheat, rice, peanuts, and dried beans, could be grown on the surface or launched in bulk from Earth. These crops would be processed into edible ingredients. These edible ingredients, the freshly grown fruits and vegetables, and packaged food items would be used to prepare meals in the galley. Dependence on the processing and preparation of bioregenerative and bulk commodity foods presents unique risks for these missions.

A mission to Mars will use prepackaged foods, similar to those that are used on ISS, for transit and may include positioning food on Mars prior to crew arrival. Prepositioned food may be 3 to 5 years old at the time of consumption. Currently, prepackaged foods have a stated shelf life of 18 months but will need a 5-year shelf life for the Mars missions. Shelf-life criteria are safety, nutrition, and acceptability. Any of these criteria can be the limiting factor in determining the shelf life of food.

Safety

Food safety is the protection of food from physical, chemical, and microbiological contamination. The food system must be designed to ensure that the initial provisions are safe from contamination and are packaged to remain safe from contamination for up to 5 years of storage in multi-environments. Good manufacturing practices, which include employee qualifications and training, sanitation, recordkeeping, process validation, and facilities and equipment maintenance and verification, are followed to prevent food contamination during processing and packaging (21CFR110, 2008).

Microbiological contamination of food can negatively affect crew health and possibly compromise crew survival. Most food items are monitored by the Johnson Space Center's (JSC) Microbiology Laboratory (as specified in JSC 16888 (publicly unavailable)) to ensure that preparation and packaging procedures result in products that conform to established microbial standards for flight foods. Table 12-1 lists the items that are tested and the associated limits.

NASA adheres to the Hazard Analysis and Critical Control Point (HACCP) system, which is a systematic and preventive approach to food safety that was developed by NASA, the United States Army Laboratory, and the Pillsbury Company in the 1960s. Both the Centers for Disease Control (CDC) and the United States Department of Agriculture (USDA) cite the implementation of the HACCP system of inspection as a principal reason why the incidence of food-borne illness appears to be declining (PBS Frontline, 2002). The use of HACCP, including the strict use of good manufacturing practices, standard operating procedures, and testing of processed foods, is associated with the prevention of food-borne illness events during space missions.

Nutrition

Adequate nutrition has two components: necessary nutrients, and energy that is in the form of calories. Without adequate nutrition, there is a risk of not being able to live a healthy, productive life. It is possible to consume enough calories without a well-balanced selection of individual nutrients. This can result in diseases that are noticeably different from those resulting from an overall insufficiency of nutrients and energy. For example, a Vitamin C deficiency may result in scurvy while a deficiency in niacin may result in pellagra. It is important that crew members who are on a long-duration mission are provided with the required level of nutrition throughout their mission. Table 12-2 summarizes the required nutritional requirements as stated in the CxP 70024, *Human-Systems Integration Requirements* document, section 3.5.1.3.1 (publicly unavailable).

Table 12-1. ***Microbiological Testing for Flight Food Production***

Area/Item	**Microorganism Tolerances**	
Food Production Area	**Samples Collected***	**Limits**
Surfaces	Three surfaces sampled per day	3 CFU/cm^2

Packaging Film	Before use	(Total aerobic count)
Food Processing Equipment	Two pieces sampled per day	
Air	One sample of 320 liters	113 CFU/320 liters (Total aerobic count)
Food Product	**Factor**	**Limits**
Non-thermostabilized**	Total aerobic count	20,000 CFU/g for any single sample (or if any two samples from a lot exceed 10,000 CFU/g)
	Coliform	100 CFU/g for any single sample (or if any two samples from a lot exceed 10 CFU/g)
	Coagulase positive staphylococci	100 CFU/g for any single sample (or if any two samples from a lot exceed 10 CFU/g)
	Salmonella	0 CFU/g for any single sample
	Yeasts and molds	1,000 CFU/g for any single sample (or if any two samples from a lot exceed 100 CFU/g, or if any two samples from a lot exceed 10 CFU/g *Aspergillis flavus*)
Commercially Sterile Products (thermostabilized and irradiated)	No sample submitted for microbiological analysis	100% inspection for package integrity

*Samples collected only on days that the food facility is in operation.
**Food samples that are considered "finished" products that require no additional repackaging are only tested for total aerobic counts.

Table 12-2. ***Nutrition Composition Breakdown***

Nutrients	Daily Dietary Intake
Protein	0.8 g/kg And ≤ 35% of the total daily energy intake And two-thirds of the amount in the form of animal protein, and one-third in the form of vegetable protein
Carbohydrate	50%–55% of the total daily energy intake
Fat	25%–35% of the total daily energy intake
Ω-6 Fatty Acids	14 g
Ω-3 Fatty Acids	1.1–1.6 g
Saturated fat	< 7% of total calories
Trans fatty acids	< 1% of total calories
Cholesterol	< 300 mg/day
Fiber	10–14 grams/4187 kJ
Fluid	1–1.5 mL/4187 kJ And ≥ 2000 mL
Vitamin A	700–900 µg
Vitamin D	25 µg

Nutrients	Daily Dietary Intake
Vitamin K	Women: 90 µg Men: 120 µg
Vitamin E	15 mg
Vitamin C	90 mg
Vitamin B12	2.4 µg
Vitamin B6	1.7 mg
Thiamin	Women: 1.1 µmol Men: 1.2 µmol
Riboflavin	1.3 mg
Folate	400 µg
Niacin	16 mg NE
Biotin	30 µg
Pantothenic Acid	30 mg
Calcium	1,200–2,000 mg
Phosphorus	700 mg And ≤ 1.5 × calcium intake
Magnesium	Women: 320 mg Men: 420 mg And ≤ 350 mg from supplements only
Sodium	1,500–2,300 mg
Potassium	4.7 g
Iron	8–10 mg
Copper	0.5–9 mg
Manganese	Women: 1.8 mg Men: 2.3 mg
Fluoride	Women: 3 mg Men: 4 mg
Zinc	11 mg
Selenium	55–400 µg
Iodine	150 µg
Chromium	35 µg

The ability of the food system to meet the nutritional requirements of a crew can only be determined when the nutritional profile of the entire space food system is known at the time at which the food is consumed. However, there has only been limited measurement of the nutritional content of the flight food items. Macronutrients and some minerals are determined chemically at the JSC Water and Food Analytical Laboratory (WAFAL). Other nutrients, such as vitamins, are currently calculated with a computerized nutrient database that was developed by the USDA and the food industry. However, the level of processing that is done by NASA can reduce the quality of the food, including its nutritional content and acceptability. In addition, it is unknown whether processed foods will maintain nutritional adequacy for 3 to 5 years.

Nutrient losses may also occur due to environmental conditions, such as the higher radiation levels that will be encountered during planetary missions. The addition of antioxidants to the food may help prevent the formation of free radicals that contribute to food spoilage (Wilson et al., 2007; Gandolph et al., 2007). In the case of a bioregenerative food system, in the absence of sufficient protection, radiation may affect the ability of plants to germinate and grow, and it may also affect their resulting functionality (Wilson et al., 2007).

During the short-duration lunar missions, it is assumed that extravehicular activities (EVAs) will be scheduled to occur not less than every other day for 8-hour periods during surface missions (NASA, 2005). As stated in the CxP 70024, *Human-Systems Integration Requirements* document, these EVAs will require no less than an additional 200 kilocalories per EVA hour above the nominal metabolic intake, with a similar nutrient composition to the rest of the diet. . Requirements for long-duration lunar or Mars missions have not been determined, but would likely be similar to those for the short-duration lunar missions.

Acceptability

Food acceptability can be defined and determined in several ways. The first way is in terms of appearance, flavor, texture, aroma, and serving temperature. Currently, flight foods are evaluated using sensory analysis, for acceptability on the ground, by a panel of 30 or more consumers. The products are rated based on appearance, flavor, texture, and aroma using a 9-point Hedonic Scale.[1] Food products must receive an overall score of 6 or higher to be included in the space food system. Similarly, prior to flight, a crew member will evaluate the foods on the 9-point Hedonic Scale. If the score assigned to a food item is less than 6.0, that food item will not be on the crew member's personal preference menu.

Product acceptability can also be affected by factors such as product formulation, product age, how the product is stored, and where the product is consumed. Menu variety and usability of the food system also contributes to food acceptability. A large variety of food items is recommended to provide the crew choices and to avoid menu fatigue. If the food is difficult to prepare or eat, the overall acceptability of the food is reduced (Smith et al., 1975).

Finally, food acceptability can also be affected by social context and the timing of meals. Food and mealtimes can play a primary role in psychological-social benefit, such as reducing the stress and boredom of prolonged space missions or promoting unity by dining together.

Resource utilization

During the development of a space flight food system, several resources must be considered including: mass, volume, power, crew time, and waste disposal capacity. Misuse of these resources may affect mission success. The balancing of resources with food quality is dependent on the specific mission. For example, the 2-week initial missions to the Moon will consider

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[1]The Hedonic Scale is used by tasting panels to indicate the extent of their like or dislike for a particular food item.

mission resource utilization more important due to the small usable volume in the vehicle. Since the missions will be shorter, nutrition and acceptability may not be as critical.

Food packaging is a major contributor to mass, volume, and waste allocations for NASA missions. Packaging is integral to maintaining the safety, nutritional adequacy, and acceptability of food, as it protects the food from foreign material, microorganisms, oxygen, light, moisture, and other modes of degradation. The higher the barrier properties of the packaging, the more that packaging can protect the enclosed food from oxygen and water ingress from the outside environment. Oxygen ingress can result in oxidation of the food and loss of quality or nutrition. Water ingress can result in quality changes such as difficulty in rehydrating the freeze-dried foods.

The current packaging that is used for the freeze-dried foods and natural-form foods for the ISS does not have adequate oxygen and moisture barrier properties to allow for an 18-month shelf life. Therefore, these foods are overwrapped with a second foil-containing package that has higher barrier properties. The packaging materials that are used for the thermostabilized, irradiated, and beverage items that are consumed on station contain a foil layer to maintain product quality beyond the required 18-month shelf life. Although the foil layer provides excellent protection, it is not compatible with all of the technologies that produce commercially sterile foods. For example, two emerging technologies – high-pressure processing and microwave sterilization – cannot use the foil package. This will require NASA to continue using the foil packaging and forego those emerging technologies, or to acquire packaging that is compatible with both of those technologies.

Tables 12-3 and 12-4 list the oxygen and water vapor permeability of the current NASA food packaging materials.

Table 12-3. ***Oxygen Permeability of Packaging Materials (CC/100IN2/DAY)***

	73.4ºF@100% Relative Humidity
Overwrap	0.0065
Thermostabilized and Irradiated Pouch	< 0.0003
Rehydratable Lid and Natural Form	5.405
Rehydratable Bottom (heat formed)	0.053

Table 12-4. ***Water Vapor Permeability of Packaging Materials (G/100IN2/DAY)***

	100ºF@100% Relative Humidity
Overwrap	< 0.0003
Thermostabilized and Irradiated Pouch	0.0004
Rehydratable Lid and Natural Form	0.352
Rehydratable Bottom (heat formed)	0.1784

The food system generates both wet and dry waste. Dry waste may include items such as dry food packaging. As it is cost prohibitive to plan on launching the trash from the lunar or Mars surface, another alternative is required for trash disposal. Although the foil layer that is within a food package protects that food from oxygen and water migration, it may provide complications if the decision is made to incinerate the trash on the lunar or Martian surface. Wet waste may include cleaning materials and wet food packaging. Because of the spoilage of food substances that are left on cleaning materials and in packaging, food system wet waste materials must be properly disposed of to limit microbial contamination to the crew.

If a bioregenerative food system is used during the lunar or Mars surface missions, some mass and volume savings will be seen from the use of less packaged foods. However, the processing and preparation equipment will contribute to the mass and volume of the habitat. In addition, the use of this equipment will require more water, power, and crew time than would be required by simply heating or hydrating packaged foods. The benefits of bioregenerative food systems will require a vigorous defense if the resources that they require are to be allocated on such resource-constrained missions.

Evidence

Safety

Good manufacturing practices, including microbiological testing of food products pre-flight, have likely prevented food-borne illness in the past. Freeze drying prevents food-borne illness by eliminating the water that is necessary for microorganisms to grow. Safe freeze-dried foods depend, at the beginning of the process, on high-quality ingredients and clean surfaces with minimal microorganism contamination. However, there still can be viable microorganisms in the food. These foods are therefore tested for viable microorganisms pre-flight. There have been instances in which freeze-dried foods did not pass microbiological testing due to contamination from mold, yeast, or bacterial pathogens. Mark Ott from the JSC Microbiology Laboratory reported at the 2006 Spring Meeting of the American Society for Microbiology, Texas Regional Branch, Wimberley, Texas, that 14 items over several years – including chicken salad and shrimp – failed to meet the microbiological testing for flight food production specifications (see Table 12-1) and, hence, were not approved for shuttle and ISS flights. Although this is a small number based on the number of samples that were tested in the JSC Microbiology Laboratory, even one food lot can result in several crew members becoming sick during a mission (Category I).

Thermally processed foods are processed to a high enough temperature for a long enough time to provide commercial sterilization. As with the freeze-dried foods, safe foods are still dependent on good HACCP practices. After processing, the thermostabilized pouches are tested for pouch integrity and swelling to determine whether adequate heat was applied to the food to produce commercial sterility (Category IV).

Nutrition

Crew members during Apollo missions often experienced reduced appetite, possibly due to a combination of effects such as fluid shifts, pressure changes, nausea, and workload. Rambaut et al. (1975) state that the importance of nutrition in the adaptation of astronauts to weightlessness has been recognized since the Gemini program. Smith et al. (1975) note that throughout the Mercury, Gemini, and Apollo missions, weight losses among the flight crews were noticed with few exceptions, including two crew members on Apollo 14. Food intake during these missions was consistently below the quantities that were necessary to maintain body weight. Although the energy intake from the National Academy of Sciences, National Research Council Recommended Daily Dietary Allowance (RDA) is 2,870 kcal/day, the mean energy intake during these missions was only 1,880 ± 415 kcal/day. Rambaut et al. (1975) also state that Apollo nutrition guidelines provided only marginal amounts of nicotinate, pantothenate, thiamine, and folic acid. The occurrence of arrhythmias in Apollo 15 astronauts was attributed to a potassium deficiency due to inadequate nutrition in the space food system (Smith et al., 1975). The potassium deficiency in this short-term mission was mitigated in later missions through potassium supplementation. Instances of scurvy, rickets, and other nutritional deficiency conditions occurred in the earlier explorer expeditions due to poor nutrition. Therefore, an unexpected deficiency of one or more nutrients in a long-duration space mission may significantly affect mission success (Category III).

Longer-term effects of space travel on nutrition have been documented through physiological changes during the 6-month-long ISS Expeditions, in which urine, blood, plasma, and serum nutrient contents and body mass were measured post-flight and statistically compared to pre-flight baselines. Of particular concern were the decreased levels of several vitamins and minerals in the urine, blood, plasma, and serum. For example, Vitamin D levels, antioxidant capacity, γ-tocopherol levels, and folate levels were all significantly lower after flight, creating concern for weight loss and associated malnutrition during ISS Expeditions 1 through 8 (Smith et al., 2005). The results detail a reduced caloric intake (around 80% of recommended intake during space flight) leading to an average of a 5% weight decrease and potentially explaining some, or all, of the measured nutrient decrease. It has also been suggested that dietary intake may have been low due to time constraints for meal preparation and consumption (Smith et al., 2005). The Skylab crews, who were required to eat enough to meet their caloric needs, preserved body mass (Thornton and Ord, 1975) (Category III). More information on inadequate nutrition through inadequate caloric intake can be found in Chapter 9 of this document.

Inadequate intake is not the only reason for inadequate nutrition. If the food loses nutrients through processing or storage, a crew member will not have adequate nutritional intake. Available data on the vitamin content of certain processed foods at various temperatures over 2 years of storage demonstrate the potential for significant vitamin loss (Kamman et al., 1981; Kim et al., 2000; Kramer, 1974; Lund, 1975; Pachapurkar and Bell, 2005). Cameron et al. (1955) compiled data on the loss of ascorbic acid, riboflavin, and thiamine over 2 years in several canned fruits and vegetables, showing vitamin losses as great as 58% in some canned products that were held at 80°F, while the same products that were held at 50°F only showed maximum losses of 38% (Category I). Therefore, nutritional loss at 3 to 5 years, which has not been studied, could likely result in inadequate nutrition in the food system (Category I).

Nutrient changes during processing and over the shelf life of processed foods include isomerization of vitamins or vitamin precursors, changes in the bioavailability of amino acids and vitamins as the food structure is broken down, and nutrient degradation, including oxidation of several vitamins and amino acids (Gregory, 1996; Chen et al., 1995; Rock et al., 1998; Dewanto et al., 2002; Graziani et al., 2003; Seybold et al., 2004). The bioavailability of vitamins may be more important than overall quantity in a food, as other components in the diet and the form of the vitamin may influence absorption and function. Therefore, the bioavailability of vitamins in individual foods may vary, making it important to have an understanding of the available nutrients as well as the overall quantity (Gregory, 1996) (Category I).

Some emerging technologies will be approved by the FDA for commercial sterility in the next few years. The two technologies with the most promise are high-pressure processing (HPP) and microwave sterilization. HPP is a method of food processing in which the food is subjected to elevated pressures (up to 87,000 psi or approximately 6,000 atmospheres), with or without the addition of heat, to achieve microbial inactivation or alter the food attributes to achieve consumer-desired qualities. Pressure inactivates most vegetative bacteria at pressures that are above 60,000 psi. HPP retains food quality, maintains natural freshness, and extends the microbiological shelf life (Balasubramaniam, 2007). Microwave sterilization is a high-temperature, short-time process in which packaged food is cooked at 265°F for 10 minutes (U.S. Army Soldiers System Center (Natick), 2004). Current thermostabilized NASA food products are cooked to about 250°F, but for a much longer time. Preliminary studies suggest that the quality of the foods is much higher using these promising technologies. Lund (1988) determined that food quality (i.e., color, texture, etc.) may provide a general indication of the nutritional loss of the food.

While lower temperatures during storage could help alleviate the storage issues, ISS and shuttle missions do not have the mass or power capabilities to provide cold storage (Perchonok and Bourland, 2002) (Category I). Currently, the commercial food industry does not require foods to have shelf lives longer than 2 years (Category III).

Acceptability

The acceptability of the food system has been linked to caloric intake and associated nutritional benefits. If food is not acceptable to a crew, the crew will not eat an adequate amount of it and will be compromised nutritionally. Large improvements and advances in space food systems were achieved during the Apollo food program. Nevertheless, the majority of the Apollo astronauts did not consume sufficient nutrients. Loss of body weight, fluids, and electrolytes were the rule, with few exceptions (Smith et al., 1975).

A thorough review of the Apollo experience was provided by Scheuring et al. in a NASA document, TM-2007-214755, *The Apollo Medical Operations Project: Recommendations to Improve Crew Health and Performance for Future Exploration Missions and Lunar Surface Operations* (not publicly available). The objective of the study was to provide evidence to modify medical requirements for future Exploration missions by identifying Apollo 7 through 17 mission medical issues. This historical database was generated based on the responses of 14 of 22 surviving Apollo astronauts to 285 questions. Among the 11 categories that were addressed, Food/Nutrition had 76 responses and eight recommendations. Scheuring et al., in addition to Rambaut et al. (1975), report that reduced food consumption may be partially attributed to a combination of physiological effects such as fluid shifts, pressure changes, nausea, issues with preparing food, issues with the water system, and workload, but acceptability of and familiarity with the food are also critical to consumption. Scheuring et al. also report that changes in the sensory perception of the food have been noted between ground-based taste test participants and Apollo and shuttle mission crew members, making it important to understand the effect of pressure and fluid shifts on sensory perception. Apollo crew members have also stated that having hot water with which to prepare hot drinks (e.g., having coffee in the morning) was important, providing them with a psychological boost (Category III).

Consistently during ISS crew debriefings (the documents are not available externally due to confidentiality), the crews have stated that their food preferences change from pre-flight to flight. Similar to the Apollo and shuttle experiences, the ISS crews have also noted that their tastes for certain foods changed in microgravity and that they may crave different foods on orbit as compared to on Earth (Category III).

ISS crews have also noted in crew debriefings that they would prefer more food variety for the length of the missions, and that they tire of certain foods over 6 months. When the menu cycle repeated after only 8 days (as opposed to the current 16-day menu cycle for ISS missions), the crews noted that there was not enough variety in the menu (document not available externally due to confidentiality). As the diets of the crew members during a mission are limited to just the available items, the long-term acceptability may decrease for some of the menu items. Vickers (1999) reports that studies that were conducted by the armed forces in the 1950s showed that most foods decreased in acceptability when they were repeatedly consumed. The degree of loss of acceptability depended on the specific food (Category III).

The next-generation NASA space vehicle, Orion, is considerably smaller than the shuttle and the ISS. For this reason, the food system for the Orion vehicle is being challenged with the possibility of no food warmer or hot water. A study conducted in 2006 at the JSC Space Food Systems Laboratory measured the acceptability of food, which is normally consumed hot, when it was hydrated with ambient water or not heated. Using a 9-point Hedonic Scale (in which food scores of 6.0 or better suggest acceptability), the study showed that the food lost about 20% of its acceptability when it was consumed at room temperature and about 17% of the food items were determined to be unacceptable. Hence, there is a risk of decreased in-flight nutrition for astronauts on an Orion vehicle due to lower acceptability and fewer foods available for the mission.

Perchonok and Antonini (not publicly available) reported at the 2008 Human Research Program Investigators Workshop on the results of an accelerated shelf-life study of seven thermostabilized items and three bulk ingredients. These items were stored at 40°F (control), 72°F (storage temperature of actual flight food), and 95°F (accelerated temperature). Sensory evaluations were conducted every 4 months for the first 2 years and every 6 months for the third year. The conclusions of the study were that the shelf lives of the thermostabilized items range from 0 months for egg products to 87 months for a representative meat product. The thermostabilization process does not result in acceptable products for all formulations. For example, thermostabilized egg products tend to be rubbery and darken in color (Juliano et al., 2007). Meat products have been thermostabilized (canned) for many years and tend to maintain their quality even after processing (Category II).

Furthermore, if food preparation takes too much crew time, the consumption of that food may also decrease (Smith et al., 1975). Providing adequate sensory attributes and ease of use (preparation difficulty and time) with respect to crew scheduling will be necessary to prevent inadequate caloric intake and associated nutritional and psychological issues (Category III).

It can be concluded that if a food system has adequate levels of acceptability, variety, and usability, crew members will consume more food during their mission.

Resource utilization

The ineffective use of vehicle resources such as mass, waste, and crew time can affect mission success. Mass of the packaged food system is based on the mass of the food and the packaging that is surrounding the food. The mass of the food is dependent on the type of food and the quantity that is required to meet the caloric requirements of a crew. Smith et al. (1975) noted that the mass of the Apollo 7 food system for the crew was 1.8 lbs. of food per person per day. By the time of the Apollo 14 mission, the mass of the food for the crew averaged 2.48 lbs. per person per day. The Apollo 8 crew, in 1968, preferred the newly added thermostabilized foods, which were referred to as "wetpack foods." According to Smith et al. (1975), the improved crew acceptance of the thermostabilized product justified the weight increase. Even with the added "wetpack foods," the Apollo food system still contained a significant number of freeze-dried foods since water from the fuel cells was available for food rehydration (Category III).

Perchonok, at the 2002 annual meeting of the International Conference of Environmental Systems (not publicly available), reported that the ISS and shuttle crew members receive about 4 lbs. of food plus packaging per person per day. A higher percentage of the food on the shuttle and the ISS is thermostabilized compared to the Apollo flights due to the higher acceptability of thermostabilized food. Since ISS uses solar panels for a power source and not fuel cells that produce water as a by-product, there is no mass advantage to using freeze-dried foods. Furthermore, the average number of calories for ISS crew members is based on the actual caloric needs of a crew member based on that crew member's body weight and height, which results in an average caloric requirement of 3,000 kcal as opposed to the 2,500 kcal that were provided to Apollo crew members. Based on mass challenges, CxP designers are considering the possibility of reducing the food system mass while still providing the crew with adequate calories (Category III).

The results of a preliminary study that was conducted at JSC by French and Perchonok suggest that the total mass of a food system may be reduced in a long-duration surface mission if that food system moves more towards a bioregenerative and bulk commodity food system. (The food system that would be used in transit between Earth and Mars would remain a packaged food system, to be compatible with the microgravity environment.). French and Perchonok, at the 2006 Habitation Conference, reported on a preliminary study – the Bulk Ingredient Menu project. The designers of this project assumed that fresh fruit and vegetables would be grown in the crew habitat on a planetary surface; however, the mass of the environmental growth chambers was not included in the project mass calculations. It was projected that some food processing would be conducted using bulk ingredients (e.g., turning soybeans into tofu and milling wheat into wheat flour for bread production). The study assumed a 600-day stay on a planetary surface with six crew members. French and Perchonok report that the mass of a food system using food preparation would be about 4,200 kg. For the same length of a surface stay mission (600 days) with a crew of six, the mass of an ISS-style food system would be about 6,600 kg (Category I).

Food packaging produces a significant amount of waste. In the course of confidential crew debriefings, the NASA *Mir* crew members stated that the overwrapped foods created a trash management problem as there were two food packages per food item for the rehydratables and natural-form foods. Although the foods are not overwrapped on shuttle missions, the trash that is produced by the food system can still be significant. Lee (2000) reports that 60% of the mass that was measured from waste on STS-99 was generated from the food system (including food, drinks, and packaging) while STS-101 demonstrated an even greater percentage (i.e., 86% of the mass). An analysis of the food waste on STS-51D showed a total trash mass of 50.7 lbs. that included 26.9 lbs. of uneaten food and 23.8 lbs. of food packaging. Eighty-five percent of the trash by volume on STS-29 and STS-30 was food packaging, and 7% of the trash volume was food (Wydeven and Golub, 1991) (Category II).

In a 2001 trade study (not publicly available), Levri et al. evaluate five potential menus for use during a Mars mission. From the study it was determined that for prepackaged foods generally 3% of the food would be left in the package if an attempt were made to eat everything. As packaging is about 9.5% of the mass of the total food system, it would therefore be expected that, at a minimum, 12.5% of the rehydrated food system on a Mars mission would become waste (Category I).

To avoid the issues that are associated with trash accumulation on a lunar or Mars surface mission, the trash will need to be disposed of. One option is to incinerate it; however, the foil layer within the food package will not incinerate completely and will leave some ash from the foil (Perchonok, 2007) (Category IV).

Several studies, which attempt to balance mass, volume, crew time, and power requirements with nutrition and acceptability, have been conducted to determine the effect of a bioregenerative food system on a lunar or Mars mission. In the Levri et al. (2001) trade study, five menus were evaluated (Table 12-5) that use Equivalent System Mass (ESM). ESM converts mass, volume, power, cooling, and sometimes crew time requirements into one mass value. The volume, power, cooling, and crew time requirements are converted to mass using equivalency factors. These equivalency factors are based on mission length and location.

The Shuttle Training Menu was similar to the menu for the shuttle and ISS food system. The various menus supplemented the Shuttle Training Menu with frozen foods, bulk-packaged snack foods, and/or salad and/or potatoes. The salad and potatoes would be grown on the Mars surface. Levri et al. (2001) determined that if only ESM was considered in choosing a menu, either case 2, case 4, or case 5 would be chosen (Table 12-6). However, the authors also concluded that non-quantifiable issues (with respect to ESM), such as food palatability and the psychological benefits of plant-crew interaction, must come into play in making a decision (Category I).

Table 12-5. ***Food System Options*** **(Levri et al., 2001)**

Case	Food System	Packaging Approach	Crop Growth
1	ISS Assembly Complete (some frozen food)	Individual Servings	Salad
2	Shuttle Training Menu	Individual and	Salad

		Multiple Servings	
3	Shuttle Training Menu	Individual Servings	Salad and White Potato
4	Shuttle Training Menu	Individual Servings	Salad
5	Shuttle Training Menu w/reduced water content	Individual Servings	Salad

Table 12-6. *Non-crew -time ESM, Crew-time ESM, and Total ESM* (Levri et al., 2001)

ESM	1 (frozen)	2 (multiple serving)	3 (potato)	4 (indiv)	5 (reduced water content)
ESM_{NCT}*	27,587	23,246	27,198	23,324	23,351
ESM_{CT}**	4,398	3,635	4,848	3,650	3,654
ESM_{TOTAL}	31,984	26,881	32,047	26,974	27,005

*Non-crew time
**Crew time

During a Lunar Mars Life Support Test Project simulation in a closed chamber, a four-person crew tested a 10-day vegetarian diet that was based on crops that were expected to be grown during long-duration missions. These crops were processed into ready-to-use ingredients outside of the chamber, leaving general cooking activities and cleanup to the crew. The general preparation and cleaning activities required 4.6 crew hours total per day. The amount of waste, which was accrued mostly from leftovers, ranged between 20% and 80%. This experience demonstrated a need for automated processes, a diverse menu, and improvements in recipe scaling based on crew size (Kloeris, 1998) (Category I).

French and Perchonok, at the 2006 Habitation Conference (not publicly available), reported that the preliminary Bulk Ingredient Menu project determined that food preparation would require, for a crew of six, about 3 hours per day. However, in addition to the 3 hours actively spent preparing food, about 6 hours per day of passive time was required for food preparation. Passive time was defined as the preparation time that did not require a crew member to constantly watch over the process, such as the time that is involved in baking. Note that only 30 minutes are set aside for crew preparation on ISS missions (Category I).

Computer-based Simulation Information

Shelf life can be defined as the time at which a product no longer maintains its specified quality. Changes in food, whether nutritionally or in quality, occur through chemical reactions and can be modeled to determine the theoretical shelf life. Actual shelf-life testing is required not only to confirm the rate of reactions, but also to determine which chemical reaction in the food will determine the ultimate endpoint of the shelf life. For example, the endpoint may be the Maillard Browning reaction[2] or the loss of a vitamin.

All chemical reactions in food adhere to the simple general rate equation of

$$-\frac{d[A]}{dT} = k[A]^n$$

where A is the quality attribute that is being measured, T is the time, k is the rate constant, and n is the reaction order (Labuza and Schmidl, 1985). Most quality reactions in food are zero or first order. Zero-order reactions exhibit a constant change in quality over time. Typical zero-order reactions ($n = 0$) are enzymatic browning, non-enzymatic browning, and lipid oxidation. Typical first-order reactions ($n = 1$) are protein and most vitamin deterioration as well as microbial growth. Although there are not many second-order reactions ($n = 2$) in food, it has been reported that, in limited oxygen, the degradation of Vitamin C is second order (Labuza, 1982).

Q_{10}, which is a measure of how the rate changes for every 10°C change in temperature, is defined as

$$Q_{10} = \frac{\text{Shelf life at temperature T°C}}{\text{Shelf life at temperature (T°C + 10)}}$$

If the color change reaction happens in half the time at 10°C higher temperature, then $Q_{10} = 2$ (Perchonok, 2002).

Since food is not a model system, it is not simple to estimate Q_{10}; but typical Q_{10} values are shown in Table 12-7. Table 12-7 shows that there is no definitive Q_{10} for a given type of food such that each food must be tested to determine its own Q_{10}. Note that a given type of food may have several Q_{10}s. The lipid oxidation may have one Q_{10} value and the Maillard browning may be a different Q_{10} (Perchonok, 2002).

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[2]The Maillard-Browning reaction is a chemical reaction, usually requiring heat, which takes place between an amino acid and a reducing sugar.

Table 12-7. Q10 Values for Various Food Preservation Methods

Food Preservation Method	Q10
Thermally Processed	1–4
Dehydrated	2–10
Frozen	3–40

With the Q_{10} values calculated, product shelf life can be projected using the formula

$$t_s = t_0 e^{-aT}$$

where:

t_s = desired shelf life
t_0 = shelf at a reference temperature
a = slope of the line equal to $\ln Q10/10$
T = temperature difference between temperature at which the shelf life, t_s, is desired and the reference temperature

Shelf-life information may be collected at a faster rate using accelerated shelf-life testing and the Q_{10} value. Accelerated shelf-life testing requires a control temperature in which no changes are expected to occur through the shelf life. The product may also be stored at the current storage temperature and an accelerated temperature, in which the reaction rates and resulting shelf life at the accelerated temperature are used to determine the shelf life at the current temperature using the Q_{10} value (Evans et al., 1981). However, the accelerated temperature may cause changes that would not normally occur in foods at regular storage temperature, such as melting, protein denaturation, and increased water activity (Labuza and Schmidl, 1985). These changes must be considered when analyzing shelf-life data.

The complexities of food structure and variety of components make food a dynamic system, which increases the difficulty in quantifying changes with kinetic models. The loss of vitamins to leaching (even when the vitamins are consumed in the leach liquid), the loss of nutrients during thermal processing, and the potential for increases in nutrient bioavailability as the food matrix is broken down during processing create an ambiguous picture of the actual nutritional content of processed foods. While the literature attempts to quantify the changes in nutritional content, the answers are not always obvious. However, the literature data provide an estimate for kinetic changes in the space food system and insight into the potential countermeasures, such as alternative processing methods and formulation interactions.

While kinetic data are available for the loss of nutrition during processing and storage, the rate constants that are provided are specific to the food and conditions in each test (Evans et al., 1981; Feliciotti and Esselen, 1957; Mulley et al., 1975; Kirk et al., 1977; Lanthrop and Leung, 1980; Rao et al., 1981; Kamman et al., 1981) (Category I). Therefore, the use of the models that are in the literature will only provide a rough estimate of the remaining nutrition if kinetic models were prepared using these data. Accurate nutrition loss data on the thermostabilized pouches that are specific to the space food system need to be acquired over a 3- to 5-year shelf life to avoid the use of a food system that has inadequate nutrition for a Mars mission. Food quality (i.e., color, texture, etc.) may provide a general indication of the nutritional loss of the food, as quality factors have a similar temperature dependence to that of many nutrients (Lund, 1988).

Risk in Context of Exploration Mission Operational Scenarios

Safety

As long as the use of HACCP (including the strict use of good manufacturing practices, standard operating procedures, and testing of processed foods) continues for packaged flight food approval, food-borne illness events should be prevented during missions. There is always a small risk of food-borne illness during flight. Once NASA builds the lunar habitat to use as a test bed for Mars missions and travels to Mars, the source of food for the crew may not be limited to only packaged food, so the risk of food-borne illness will increase.

During surface preparation of fresh food, safety is no longer ensured as it is through ground operations. Consideration must therefore be given to food safety from microbial, chemical, and physical sources during food processing and preparation on the surface to prevent adverse effects on crew health and performance. If fresh fruits and vegetables are consumed without a heat step (cooking), there is a potential for food contamination and, hence, food-borne illness. There may be a need to wash or sanitize the fresh fruits and vegetables. The risk still needs to be quantified for a closed environment, especially in light of the fact that from 1991 to 2002, there were several produce-related *Escherichia coli* O157:H7 outbreaks reported for field-grown produce (Aruscavage et al., 2006).

If the packaged food or bulk ingredients are prepositioned on the Mars surface, there is a risk that the food will have been compromised prior to the arrival of the crews. Packaging can be torn or the food may be adversely affected by the Martian environment.

Fresh food and bulk ingredients processing and subsequent preparation of meals from edible ingredients and packaged foods during the long-duration lunar and Mars missions will provide the crew with more variety and fresh foods. However, during these processes, it is necessary to reach a certain temperature/time combination to ensure safety and functionality. It is being proposed by mission designers that the lunar habitat will maintain an 8-psi atmospheric pressure. Heat and mass transfer are affected by partial gravity and reduced atmospheric pressure. At an 8-psi pressure, the boiling temperature for water is 181°F. Consideration must therefore be given to changes in the environment and the required processing equipment and procedures to ensure safe food processing on the lunar surface.

It is critical to quantify and reduce the risk of food preparation and processing safety before sending out human crews on a long-duration lunar mission. This risk could delay a long-duration lunar mission even if all other elements of the mission are ready. Mission loss or major impact to post-mission crew health would likely occur if this risk is not quantified and reduced.

Nutrition

Although it is common for crew members to lose weight during ISS missions, the crew members have still been able to perform their duties. The degree of weight loss for the 6-month lunar missions is assumed to be similar to that for the ISS missions. However, for the Mars missions, the food will need to have a shelf life of about 5 years (as opposed to 18 months for ISS missions) to accommodate the 1,000-day Mars mission. The packaging will also have to maintain its physical and chemical barrier properties for 5 years. Any pre-positioning of the food or delay in the consumption of the food will potentially decrease the nutritional content of the food even more. With no resupply options, it is critical to quantify and potentially reduce the risk of inadequate nutritional content of the food prior to a Mars mission. Once the crew members begin their mission, they will have no opportunity to mitigate a loss of nutrition with resupplied foods or supplements.

The lunar short-duration missions may require that each crew member perform 8-hour EVAs every other day. If the crew members cannot access adequate nutrition during the EVAs, the risk of loss of performance can increase.

Unique to space travel are nutrient losses due to space radiation. Although the extent of loss is unknown, one flight study is currently examining the nutritional loss of five food items that were stored on board the ISS for about 2 years. Ground controls are also being analyzed to help determine the effect of radiation. There is also a potential risk of nutritional loss of the chamber-grown fresh fruits and vegetables and the bulk ingredients that may be launched for use in food processing and preparation during surface missions.

The use of bulk ingredients and fresh fruits and vegetables on the lunar and Martian surfaces can provide the crew with a variety of fresh foods and associated nutrients. These fresh foods should provide at least some of the vitamins that may be lost over time in the processed foods, thereby enhancing the nutritional intake of the crew members and their associated health and well-being while reducing the risk. While the processing of bulk ingredients and preparation of edible ingredients and fresh vegetables into meals can provide some of the lost nutrients, any failure in the growth, processing, and preparation of the foods could increase the risk of loss of nutrition. The overall risk of this type of food system has not been quantified yet.

Acceptability

Although the acceptability of the food, including its variety and usability, is important in the 6-month ISS and lunar missions, it will be critical in the 1,000-day Mars missions. For the Mars missions, as the acceptability of the food system must be ensured for 5 years, enough variety and ease of use must be provided to ensure that the crew consumes adequate quantities throughout the period. With the addition of food processing and preparation during surface missions, there is an increased risk that the additional crew time that will be involved will counteract the increased acceptability of the overall food system. This risk could delay a Mars mission even if all other elements of the mission are ready. Mission loss or major impact to post-mission crew health would likely occur if this risk is not quantified and reduced.

The addition of freshly grown fruits and vegetables may increase the acceptability of the lunar and Mars mission food systems. These fresh foods would increase the acceptability of the food system by introducing bright colors, crunchy textures, and fresh aromas, thus encouraging more caloric intake and boosting crew morale by creating a more familiar food system in a hostile and unfamiliar environment.

Resource utilization

The Orion food system is being challenged to reduce the mass due to the smaller Orion vehicle. The high volumes of packaging material that will be required to keep food safe, nutritious, and acceptable as well as the power and weight requirements for heating the water and food will need to be minimized to meet the mass requirements. The challenge will be to bring the mass from its current level of 4 lbs. per crew member per day to 2.5 lbs. per crew member per day; that is, to the mass of the Apollo food system. It is not obvious that this goal is attainable; moreover, as noted previously, the Apollo crews were not provided with adequate calories. The variety of foods provided is also at risk because the galley equipment (e.g., hot water and the food warmer) may be removed from the Orion manifest. Without food mass reduction, other systems may not be able to launch their required equipment.

There is a further risk that radiation or simply age may affect the functionality of the bulk ingredients that are launched for food processing during a Mars mission. For example, the soybean proteins may chemically change, resulting in a reduced yield in the production of tofu. As resupply will not be an option for Mars missions, it is especially critical that the food system be robust in its use of resources for 3 to 5 years. This includes the packaged food system and the bioregenerative food system. There is a danger that the packaged food system may be too high in mass. There is also a risk that acceptable food may not grow on Mars or the moon, given the reduced gravity, available water, radiation, and other aspects of the growing environment. Moreover, the equipment may not work or the water quantities may be inadequate for food hydration, processing, or preparation. Finally, there is the risk that the bioregenerative food system could require too much crew time, or that there will be too much food and packaging waste during a Mars mission.

It is worth repeating that any of these constraints on the system could delay a Mars mission, even if all other elements of the mission are ready. The risks increase with the increased length of the Mars mission; longer-term effects of radiation, especially during transit; and the lack of resupply.

Conclusion

It is a possible that on a lunar or Mars mission crew health and performance will be compromised without an adequate food system. In developing future NASA food systems, a balance must be maintained between the use of resources (e.g., power, mass and crew time) and the safety, nutrition, and acceptability of the food system to provide an adequate food system. Each of the four components – safety, nutrition, acceptability, and resource utilization –may take on different priorities based on mission duration and distance from the Earth. The incorporation of fresh foods and/or food processing and food preparation during long-duration missions may increase the risk in safety and resource utilization, but it may decrease the risk of inadequate nutrition and acceptability.

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